APPLE DAMAGE IN BULK BINS DURING SEMI-TRAILER TRANSPORT

E. J. Timm, G. K. Brown, P. R. Armstrong

ABSTRACT. *Each year a majority of the U.S. apple crop is transported in bulk bins on semi-trailers and trucks from the orchard to a storage facility or central packing house. During the transportation process, mechanical damage such as bruises, abrasions, cuts, and punctures can occur, causing a decrease in fruit grade. Tests were conducted in Michigan to identify the magnitude of damage incurred by apples in bulk bins during semi-trailer transportation on a rough interstate highway. Five bulk bin designs (two hardwood, one plywood, and two plastic), two trailer suspension systems (steel-spring and air-cushion), and two trip distances [55 and 110 km (34 and 68 mile)] were evaluated. Damage-free apples were used in all tests and accumulated damage was measured. Test fruit positioned in the middle of each bin had similar bruise and abrasion damage levels regardless of the bin design, suspension system, or trip distance. Abrasion damage on the sidewall test apples varied among bin design, suspension system, and trip distance. Abrasion damage on sidewall test fruit was significantly less on the air-cushion system. The plastic bins had much less abrasion damage on the sidewall test fruit than did the hardwood and plywood bins. The range of abrasion damage on the sidewall test apples was 0.6 to 65%. Sidewall fruit grade ranged from 71.3 to 100.0% U.S. Extra Fancy.*

Vibration data collected for both trailer suspension systems was used to develop a power spectral density representation of the load input vibration. A 60-min trip simulation on a computerized vibration table was conducted for the steel-spring suspension system using the five different designs of bulk bins. The percentage of apples having abrasion damage was comparable to levels from actual highway tests. Overall, the U.S. apple industry can maintain higher apple quality if bulk apples are transported in plastic bins of these designs and on semi-trailers having air-cushion suspension.
Keywords. *Apple, Bin, Bruise, Abrasion, Suspension, Transportation, Distance, Vibration.*

From the time apples are picked from the tree until they reach the consumer, a series of mechanical handling operations present opportunities for bruising or other mechanical damage to occur. Mechanical damage such as bruises, abrasions, cuts, and punctures are irreversible, and have a cumulative effect with each step of the handling process. The resultant effect of mechanical damage is lower grade, quality, and income to both the grower and packer.

The methods by which fresh market apples are handled are similar throughout the U.S. apple industry. During the harvesting operation the apples are hand-picked and placed into bulk bins. Once the apples are in the bulk bins they are either transported by forklift, tractor-mounted forklifts, or self-loading bin carriers directly to the packing house or are moved to a staging area. At the staging area the bins are loaded onto trucks or trailers and transported to a storage facility or central packing house.

Wood bins have been the prevalent type of bulk bin used in the U.S. apple industry. In the eastern United States, the apple industry predominately uses a hardwood bulk bin [400 kg (900 lb) capacity] for transporting and storing of apples. On the west coast, where a large percentage of the U.S. apples are grown, the preferred bulk bin has been plywood [450 kg (1,000 lb) capacity]. Several different types of variations in design exist for both hardwood and plywood bins. The main advantages of the wood bin are its strength and low cost. However, some disadvantages of wood include; weathering, rough surfaces, absorption of moisture and chemicals, and poor ventilation. Research has shown that the construction, condition, and type of wood finish on the bin can have an adverse effect on the quality of fruit. Bins that rack during transport and are made from rough-sawed lumber can cause bruising and abrasions on fruit (Maindonald and Finch, 1986; O'Brien et al., 1980). Burton et al. (1989) demonstrated that foam padded liners in wooden bulk bins reduced bruising in apples up to 40% during handling and transport. Armstrong et al. (1991, 1992) found that during truck transport, plywood bulk bins generally caused less bruise damage to apples than did hardwood bins.

With the recent introduction of plastic bins in the U.S. apple industry, growers and packers are reluctant to switch from wood to plastic because of several key factors. One of the important factors is the initial cost of the bin. However, many distinct advantages exist with a plastic bin. Some of them include resistance to weather, lightweight, non-absorbing material, and smooth surfaces. Waelti (1994)

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found that apples in plastic bins cool four times as fast as those in plywood bins and fruit weight loss was less over an extended period of storage. As the plastic bin becomes more prevalent in the U.S. apple industry, questions such as service life of the bin and quality of the fruit after it has been handled will become known facts.

One of the mechanical handling processes that can be detrimental to the quality of the fruit is transportation. Each year a large percentage of the U.S. apple crop is transported in commercial bulk bins on semi-trailers from the orchard staging area to a storage facility or central packing house. During the transport process the truck bed can transmit vibration and shock into the bin that can cause damage to the fruit. Road roughness, truck suspension type, number of axles, trailer bed length, axle position, speed of travel, load weight, and bulk bin type are all factors that interact during the transport process and can produce acceleration levels that damage the fruit.

The movement of the truck bed can be characterized by a frequency spectrum envelope based on the random vertical acceleration of the truck bed and can be represented by a power spectral density (PSD) curve. Pierce et al. (1992) studied the differences between the ride quality of air-cushion and steel-spring suspensions. They found that the PSDs for air-cushion were generally higher between 1 and 3 Hz compared to steel-spring PSDs. Above 3 Hz, the PSDs for steel-spring suspensions were several magnitudes higher than for the air-cushion. Research on suspension types found that less damage occurred on fruit being transported on air-cushion systems compared to steel-spring suspension (O'Brien et al., 1963, 1969; Maindonald and Finch, 1986; Armstrong et al., 1991, 1992).

Objectives

Although the plastic bin has several advantages over wooden bins, little information exists on the quality of the fruit after it has been handled in a plastic bin. A transportation experiment was conducted to determine what effect plastic bins have on the quality of the fruit compared to wooden bins. Five bulk bin designs (two hardwood, one plywood, and two plastic), two trailer suspension systems (steel-spring and air-cushion), and two trip distances [55 and 110 km (34 and 68 mile)] were evaluated.

The specific objectives of our study were to:

- Determine differences in damage levels resulting from semi-truck transportation of apples in several different types of commercial bulk bins.
- Compare the difference in damage levels on fruit transported on conventional steel-spring versus air-cushion suspension systems.
- Determine if the length of trip has any effect on the damage level.
- Collect vibration data for each of the suspension systems during the test and develop a PSD representation of the load input vibration.
- Determine if a 60-min trip simulation using the PSD representation as the input on a computerized vibration table gives similar damage results compared to the actual highway tests.

Materials and Methods

Fruit

The study required measuring the damage on apples that occurred in bulk bins during semi-trailer transport. The apples used in the transportation test to access damage were 70 to 82 mm (2 3/4 to 3 1/4 in.) diameter, 'Golden Delicious' variety [average firmness 67.1 N ± 4.1 N (15.1 lbf ± 0.9 lbf)]. This variety was selected because it is quite susceptible to bruising, bruises and abrasions are easy to see, and can be easily recognized and retrieved among red fruit. The apples were carefully hand-picked at the Michigan State University (MSU) Clarksville Horticulture Experiment Station, placed in foam cell trays (20 cells/tray), and packed in cellmaster cartons (80 apples/carton) in the orchard. This procedure was followed in order to minimize any bruising that may occur from transporting the apples to the storage facility.

At the storage facility the cartons were randomized to remove bias due to tree conditions and picker handling. The apples were then individually weighed, discarded if they did not fall into a weight range of 0.15 to 0.23 kg (0.33 to 0.51 lb), repacked into the cellmaster cartons, and placed into cold storage (1°C, high RH) until further use.

Bulk Bins

The five types of commercial bins used in the transport tests are described below and illustrated in figure 1. All bins were new except for the hardwood bins which were approximately five years old. A total of eight bins, two hardwood, two plywood, and four plastic, were used in each test.

1. Two Stringer Michigan Hardwood Bin. This bin is constructed entirely from rough sawn oak hardwood with triangular corner posts and two bottom stringers. Boards [24 × 127 mm (0.9 × 5.0 in.)] are nailed to the stringers [64 × 94 mm (2.5 × 3.7 in.)] to form the bottom of the bin. The side walls are constructed out of boards [16 × 152 mm (0.6 × 6.0 in.)] nailed horizontally to the corner posts with gaps of approximately 13 mm (0.5 in.) between the boards to allow for air ventilation and water dumping. Inside dimensions of the bin are 990 × 1140 × 690 mm (39 × 45 × 27 in.).
2. Three Stringer Michigan Hardwood Pallet Bin. The pallet bin is constructed with triangular cornerposts lap jointed and bolted to two outside bottom stringers [38 × 87 mm (1.5 × 3.4 in.)]. A third stringer is positioned under the middle of the bin. All three stringers are held together with three bottom deck boards [18 × 127 mm (0.7 × 5.0 in.)] which form the base of the pallet. Boards approximately 16 × 152 mm (0.6 × 6.0 in.) are nailed horizontally to form the sidewalls. On two opposite inner sidewalls a single board is fastened vertically to the horizontal boards and bolted to the stringer. Inside dimensions of the bin are 990 × 1140 × 690 mm (39 × 45 × 27 in.).
3. West Coast Plywood Bin. This bin is constructed from C-C plugged exterior grade Douglas fir plywood with triangular corner posts and three bottom stringers [64 × 89 mm (2.5 × 3.5 in.)]. The sidewalls are constructed from 15 mm (0.6 in.)

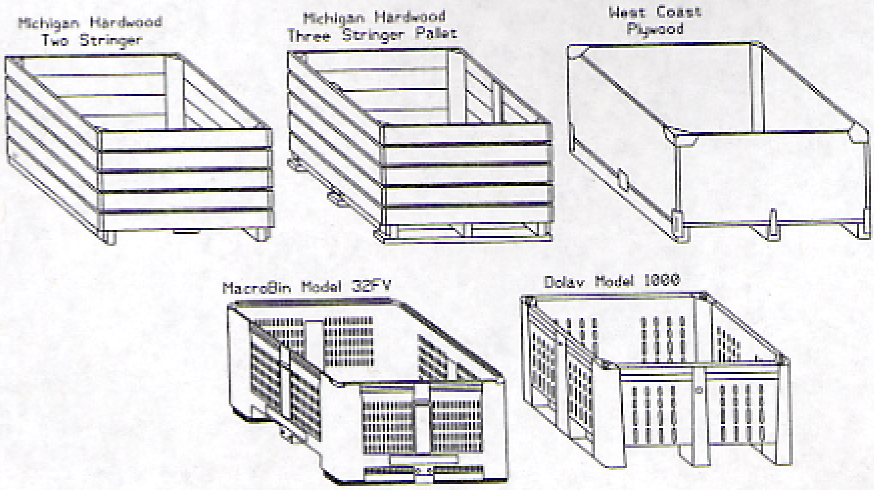

Figure 1–Hardwood, plywood, and plastic bins used in the highway transportation, bin resonance, and simulated highway transportation tests (drawings are only representations and are not to scale).

plywood. The bottom can be either a 16, 19, or 25 mm (0.6, 0.7, or 1.0 in.) plywood. We tested both the 16 and 19 mm (0.6 and 0.7 in) bin bottom. The fasteners used to construct the bin consisted of nails, glue, metal corner brackets, and metal box to stringer brackets. There are 32 routed slots approximately 19 × 152 mm (0.7 × 6.0 in.) located in the bottom of the bin for water and air flow. Inside dimensions of the bin are 1 190 × 1 190 × 610 mm (47 × 47 × 24 in.).

4. MacroBin Series 32. The MacroBin is a one piece, high-pressure injection molded plastic bin manufactured from high-density polyethylene plastic (HDPE). This monolithic rectangular bin has four double wall corner posts and four vertical center posts. A 160 mm (6.3 in.) bottom stringer connects the corner post to the center post on the shorter sidewalls. This allows for four-way forklift entry and rotation of the bin. There are 224 rounded rectangular 10 × 50 mm (0.4 × 2.0 in.) slots located on the bottom of the bin, 110 on each of the smaller dimensioned sidewalls, and 120 on the larger dimensioned sidewalls. Inside dimensions of the bin are 1 050 × 1 140 × 630 mm (41 × 45 × 25 in.) (Marco Plastics Inc., 2250 Hunting Drive, Fairfield, CA 94533).
5. Dolav model 1000 with vents. The Dolav bin is a rigid one-piece rectangular bin manufactured from HDPE. It has four corner posts and four vertical center posts on the sidewalls. Two 105 mm (4.1 in.) wide bottom stringers connect the center post on the longer sidewalls to two of the corner posts which allows for four-way forklift entry and rotating of the bin. There are 70 rectangular 15 × 30 mm (0.6 × 1.2 in.) slots located on the bottom of the bin. The smaller dimension sidewalls have 16 rectangular slots that are 10 × 50 mm (0.4 × 2.0 in.) and 16 that are 10 × 80 mm (0.4 × 3.1 in.). The larger sidewall has 44 rectangular slots. Inside dimensions of the bin are 915 × 1 120 × 610 mm (36 × 44 × 24 in.) (IMCO Group Inc., 505 Eighth Ave., New York, NY 10018).

Semi-trucks and Trailers

Two different suspension-type semi-trucks and trailers were used for the transportation test. The first semi-truck and trailer consisted of a tandem axle tractor equipped with steel-spring suspensions and conventional fifth-wheel along with a 14.6 m (48 ft) long × 2.5 m (8 ft) wide steel-spring suspension trailer with close-spaced sliding tandem axles in a full rear position (PBA-NF248, Fruehauf Corp., Southfield, MI 48076). The second semi-truck and trailer consisted of a tandem axle tractor equipped with air-cushion suspensions, conventional fifth-wheel, and a 14.6 m (48 ft) long × 2.5 m (8.0 ft) wide air-cushion suspension trailer with fixed wide tandem axles [3.0 m (10 ft) between centers] (GPWSAR-245, Great Dane Trailers Inc., Savannah, GA 31402).

Highway Transportation Test

The initial setup of the transportation tests involved having each semi-trailer loaded with utility grade apples at a local apple packing house. The load configuration for each semi-trailer consisted of two rows of 13 bins stacked 2 high for a total of 52 bins. The last eight bins located on the rear of the trailer consisted of firm utility grade 'Red Delicious' apples. The estimated weight for each load was approximately 21.2 t (23.4 ton). Each semi-truck and trailer was then driven to a state safety rest area. The rest area allowed us to load and unload bins and prepare test bins, with easy access to the interstate highway. At the rest area, the eight bins of Red Delicious on the rear of the trailer were unloaded and used to fill the test bins.

Prior to preparing the test bins for each transport test, 18 cartons (16 test, 2 control) of the Golden Delicious test fruit were examined for obvious cuts, punctures, abrasions, and bruises, and marked so that previous damage due to harvesting, sorting, and transporting to the preparation site would not be interpreted as damage incurred from the actual test. In each test bin the test apples were placed in the center and along two sides and were simultaneously surrounded by the firm, utility grade, Red Delicious apples. The test apples in the center were placed in the bin in layers to form a round column of 80 apples (1 carton) from top to bottom. All the test apples on the sides were placed in contact with the sidewalls to form a column of 40 apples from top to bottom. After each test bin was filled with the 160 test apples (2 cartons), it was carefully loaded on the rear of the semi-trailer with a forklift. The bin placement on the semi-trailer and apple position in the bin are shown in figure 2. Each stack of bins was strapped down in order to secure the load.

The test load was then driven from the rest area over a selected route of rough divided highway and back to the rest area: The section of highway driven was selected based upon its proximity to the apple growing region in Michigan, location of the state safety rest area and the condition of the road. The surface condition of the road based upon a 1993 Sufficiency Rating of the Michigan State Trunkline Highways was rated as poor (Michigan Department of Transportation, 1993). Fourteen bridges (highway bridges over roads and rivers) were crossed during the round trip. During each test the driver tried to maintain an average speed of 105 km/h (65 mph) while on the highway. Total distance for the entire route was approximately 55 km (34 mile) and took 45 min of driving time. The long trip consisted of driving the complete route twice. After returning to the rest area, the test bins were carefully unloaded from the trailer and the test apples were removed and placed back into cellmaster cartons. The 16 cartons of test apples along with the 2 control cartons were then transported back to the MSU Clarksville Horticulture Experiment Station and placed into cold storage until they were assessed for damage. Each test was performed only once due to the time to prepare test bins and load and unload the bins on the semi-trailers.

Damage Assessment

Damage incurred during each transportation test was measured according to USDA Apple Grades (USDA, 1964) based only on mechanical injury (abrasion, bruise, cut, puncture). The fruit can be divided into five grades—U.S. Extra Fancy, U.S. Fancy, U.S. No. 1, U.S. Utility, and Reject. Each bruise or abrasion was given a rating of A, B, C, D, or E corresponding to its diameter as judged using a set of circular discs. Bruises and abrasions smaller than 6.4 mm (1/4 in.) diameter were not counted. The following list below details the bruise and abrasion category and its diameter range.

Bruise and Abrasion Rating	Diameter Range [mm (in.)]
A	6.4 > Diameter ≤ 12.8 (1/4 > Diameter ≤ 1/2)
B	12.8 > Diameter ≤ 19.0 (1/2 > Diameter ≤ 3/4)
C	19.0 > Diameter ≤ 22.0 (3/4 > Diameter ≤ 7/8)
D	22.2 > Diameter ≤ 31.8 (7/8 > Diameter ≤ 1 1/4)
E	Diameter > 31.8 (Diameter > 1 1/4)

A computer program to analyze data from previous studies was used to summarize the data. Data from each test bin was analyzed according to bin type (hardwood, plastic, plywood), truck suspension (spring or air), trip distance (short or long), bin position (top or bottom), and fruit position (side or middle). The data summary included a detailed analysis of the type, number, and size of damage for each test.

Highway Vibration Data

During each of the highway transportation tests, vibration data was collected. Two accelerometers (model VM 10205, Vibra Metrics Inc.) were rigidly mounted to the left and right rear of each semi-trailer. Data was recorded on a PC-based Techstation model TS16 datalogger (Onsite Instruments, 855 Maude Ave., Mountain View, CA 94043) during each of the transportation trips. To simplify the data collection, the recorder was triggered on and off manually to sample road vibration every 10 s. Vibration data for sections of highway where the truck and trailer were travelling at a speed below 90 km/h (55 mph) was not collected. Each sampling period consisted of 1.28 s of continuous data collected at a sampling rate of 800 Hz. Approximately 150 to 200 sample periods of road vibration data were collected for each trip.

The road vibration data for each trip was reduced to a PSD representation by performing a Fast Fourier Transform (FFT) on each sample period (Press et al., 1989). Power density may be defined as the variance of the RMS amplitude at a given frequency about a mean value of zero g's. The PSD plots were constructed for each trip using the following relationship (Brandenberg and Lee, 1985).

$$PSD_{(f)} = \frac{\sum_{1}^{N} RMS_{(f)}^{2}}{N}$$

where

PSD = power spectral density (g^2/Hz)
N = sample periods
RMS = root mean square acceleration value (g)
f = frequency (Hz)

Bin Resonance

To determine the resonant frequency of each of the five bin types, they were filled with utility grade apples and placed on a computerized vibration table controlled by a Lansmout System Station (Lansmont Corporation, Monterey, Calif.). The resonance of each bin was determined by setting the table controller for a sinusoidal sweep at 0.5 peak g's (ASTM, 1992a). The sweep began at 3 Hz and logarithmically increased to approximately 100 Hz. The range of resonant frequency (frequency range over which the apples began and stopped bouncing) and the peak resonance (frequency which caused the most movement to the apples) was recorded manually and also with a video camera.

Simulated Highway Transportation Test

A laboratory test was conducted in accordance to ASTM standard D 4728-91, method A (ASTM, 1992b), to determine if a simulated highway transportation test would provide similar apple damage results compared to the actual highway test. Using the four PSD curves calculated from the vibration data collected from the right and left rear side of the steel-spring semi-trailer during each trip, a

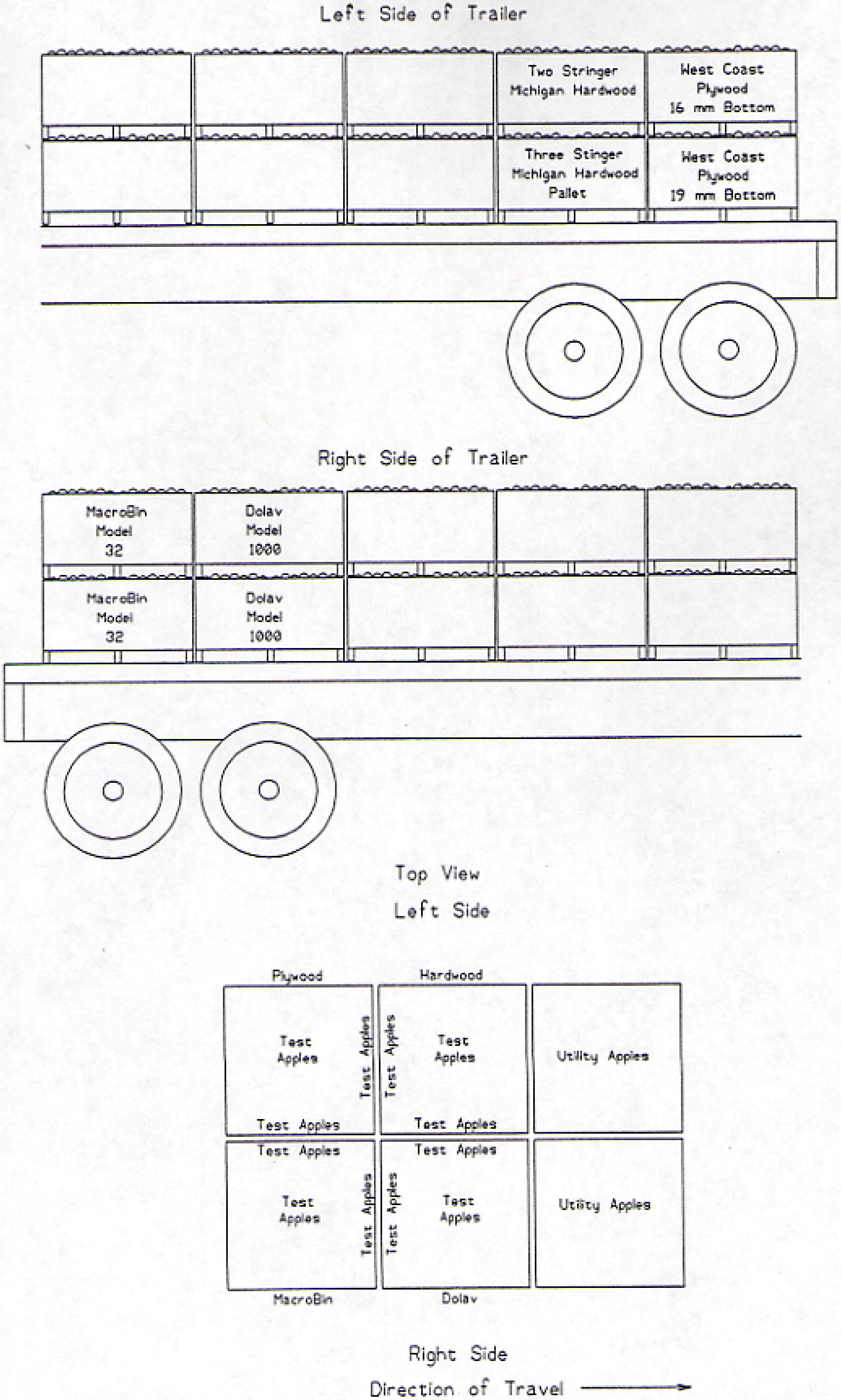

Figure 2–Stacking location and position of the test bins and location of the test apples during the highway transportation tests.

single worst case PSD curve was constructed by selecting the maximum g^2/Hz value at each discrete frequency from the four curves. A 60-min trip simulation using the worst case PSD curve as the input to the computerized vibration table was conducted with all five different designs of bulk bins. This type of input and the associated damage that occurred in each bin during the actual highway transportation trip should give the worst case trip scenario and provide a wide range of apple damage associated with each bin design. Each bin was placed on the table and prepared for testing as previously described in the transportation tests. No replications were completed due to time constraints and test apple availability. The test apples were evaluated for damage as previously described.

Results and Discussion

Highway Transportation Tests

The damage assessment of the test fruit from the highway transportation tests was analyzed by separating the data into two groups (middle and side fruit) and presenting the means for fruit quality (tables 1 and 2). The column of test fruit (80 fruit) in the middle of each bin and on the sidewalls (40 fruit per side) was analyzed as four replications of 20 fruit. Initial analysis of data for the top and bottom bins showed no significant difference in fruit quality, therefore data from each of the bin types was pooled in the final analysis to give a total of eight replications per bin type and fruit location.

Damage incurred by the control fruit during transport to and from the test site was very minimal and was not incorporated into the final analysis of the test fruit. The control fruit averaged 2.0% bruised fruit, 0.0% abrasion damage, and graded 100% Extra Fancy.

Fruit quality for the apples positioned in the middle of the bin was essentially the same for each of the highway transportation tests (table 1). Suspension type affected the percent of undamaged fruit (OK), abrasion damaged (ABR), and cut and punctured (C&P). The undamaged fruit for the short and long trip on the steel-spring semi-trailer ranged from 85.0% for the MacroBin and plywood bins to 91.3% for the Dolav bin. On the air-cushion trailer, the

Table 1. Quality of test fruit positioned as a vertical column in the middle of each test bin

Trailer Suspension	Bin Type	Trip Distance	OK* (%)	Fruit Quality (Middle of Bin) BRU* (%)	ABR* (%)	C&P* (%)	EF* (%)
Spring	Hardwood	Short	85.6 ab	12.5 ab	0.6 a	1.3 a	96.3 ab
	Dolav		91.3 ab	6.3 b	1.3 a	1.3 a	98.8 ab
	Macro		88.8 ab	9.4 ab	0.6 a	1.3 a	98.1 ab
	Plywood		85.6 ab	12.5 ab	1.3 a	1.3 a	96.3 ab
Spring	Hardwood	Long	90.6 ab	6.3 b	2.5 a	0.6 a	98.1 ab
	Dolav		87.5 ab	7.5 ab	2.5 a	3.1 a	96.3 ab
	Macro		85.0 ab	10.0 ab	1.9 a	3.1 a	95.0 ab
	Plywood		85.0 ab	11.3 ab	2.5 a	2.5 a	95.0 ab
Air	Hardwood	Short	81.3 b	16.3 a	1.3 a	1.3 a	93.8 b
	Dolav		91.3 ab	7.5 ab	0.0 a	1.3 a	98.1 ab
	Macro		91.9 a	6.9 ab	0.6 a	0.6 a	99.4 a
	Plywood		90.6 ab	8.8 ab	0.6 a	0.0 a	100.0 a
Air	Hardwood	Long	93.8 a	4.4 b	1.3 a	1.3 a	98.1 ab
	Dolav		87.5 ab	11.3 ab	0.0 a	1.3 a	98.8 ab
	Macro		95.0 a	4.4 b	0.0 a	0.6 a	98.1 ab
	Plywood		93.1 a	6.9 ab	0.0 a	0.0 a	97.5 ab
Analysis of Variance							
Suspension			†	NS‡	§	†	NS
Bin			NS	NS	NS	NS	NS
Suspension × bin			NS	NS	NS	NS	NS
Distance			NS	NS	NS	NS	NS
Suspension × distance			NS	NS	†	NS	NS
Bin × distance			†	†	NS	NS	NS
Suspension × bin × distance			NS	NS	NS	NS	NS

* OK = undamaged fruit, BRU = bruise damaged fruit, ABR = abrasion damaged fruit, C&P = cut and puncture damaged fruit, EF = Extra Fancy fruit.
† Significant at $P < 0.05$.
‡ Nonsignificant.
§ Significant at $P < 0.01$.
NOTE: Mean separation within columns by Duncan's multiple range test, $P = 0.05$, df = 112.

Table 2. Quality of test fruit positioned against the sidewall of each test bin

Trailer Suspension	Bin Type	Trip Distance	OK* (%)	Fruit Quality (Middle of Bin) BRU* (%)	ABR* (%)	C&P* (%)	EF* (%)
Spring	Hardwood	Short	35.6 f	13.8 ab	56.9 a	3.8 abcd	75.0 cd
	Dolav		86.9 ab	10.0 b	3.1 d	0.6 cd	96.9 ab
	Macro		85.0 abc	12.5 ab	1.9 d	1.3 bcd	96.3 ab
	Plywood		68.8 d	6.3 b	23.1 c	4.4 abc	89.4 b
Spring	Hardwood	Long	30.0 f	8.8 b	65.0 a	0.6 cd	71.3 d
	Dolav		71.9 d	11.9 ab	18.1 c	1.3 bcd	93.8 ab
	Macro		76.9 bcd	13.8 ab	5.0 d	5.0 ab	94.4 ab
	Plywood		51.3 e	15.0 ab	33.8 b	6.9 a	80.0 c
Air	Hardwood	Short	73.8 cd	21.9 a	5.0 d	0.6 cd	93.8 ab
	Dolav		88.1 ab	10.6 b	1.9 d	0.0 d	98.1 a
	Macro		87.5 ab	10.6 b	2.5 d	0.0 d	97.5 a
	Plywood		87.5 ab	10.0 b	1.9 d	0.6 cd	96.9 ab
Air	Hardwood	Long	84.4 abc	12.5 ab	2.5 d	0.6 cd	96.9 ab
	Dolav		91.3 a	75 b	1.3 d	0.0 d	100.0 a
	Macro		88.1 ab	10.0 b	0.6 d	1.3 bcd	96.9 ab
	Plywood		87.5 ab	11.9 ab	1.3 d	0.6 cd	97.5 a
Analysis of Variance							
Suspension			†	NS‡	†	†	†
Bin			†	NS	†	§	†
Suspension × Bin			†	NS	†	NS	†
Distance			§	NS	†	NS	NS
Suspension × Distance			†	NS	†	NS	§
Bin × Distance			NS	NS	NS	NS	NS
Suspension × Bin × Distance			NS	NS	NS	NS	NS

* OK = undamaged fruit, BRU = bruise damaged fruit, ABR = abrasion damaged fruit, C&P = cut and puncture damaged fruit, EF = Extra Fancy fruit.
† Significant at $P < 0.05$.
‡ Nonsignificant.
§ Significant at $P < 0.01$.
NOTE: Mean separation within columns by Duncan's multiple range test, $P = 0.05$, df = 112.

undamaged fruit ranged from 81.3 to 95.0% for the same bins, respectively. Bruised fruit (BRU) ranged from 4.4 to 16.3% and was not significantly affected by suspension type, bin type, or trip distance. Most of the bruises (79.2 to 100%) were classified as category A bruises [6.4 mm > Diameter ≤ 12.8 mm (1/4 in. > Diameter ≤ 1/2 in.)] with the remaining bruises (0.0 to 20.9%) classified as category B bruises [12.8 > Diameter ≤ 19.0 mm (1/2 in. > Diameter ≤ 3/4 in.)]. Overall abrasion damage was slightly higher for the steel-spring suspension compared to the air-cushion, however, no significant difference was found among bin type and trip distance. Abrasion damage ranged from 0.0 to 2.5%. Cut and puncture damage averaged 1.8% for the steel-spring suspension compared to 0.8% for the air-cushion suspension with no significant difference among bin type and trip distance. The percent of fruit that graded Extra Fancy ranged from 93.8 to 100% and was not significantly affected by suspension type, bin type, or trip distance.

Overall quality for the fruit positioned on the side of the bin was much lower compared to the fruit in the middle (table 2). The percent of undamaged fruit was significantly affected by suspension type, bin type, trip distance, and the interactions suspension × bin and suspension × distance. In the steel-spring suspension tests the plastic bins had a much higher percent of undamaged fruit than did the wood bins. Undamaged fruit for the steel-spring suspension tests ranged from 30.0% for the hardwood bin to 86.9% for the Dolav bin compared to a range of 73.8 to 91.3% for the air-cushion tests. Bruise damage was comparable among treatments, as no significant difference was found between suspension type, bin type, and trip distance. Abrasion damage was significantly higher for the fruit transported on steel-spring suspension, in wood bins, and the longer trip distance. The abrasion damage in the wood bins for the steel-spring suspension tests ranged from 23.1 to 65.0% for the plywood and hardwood bins compared to 1.9 to 18.1%

for the plastic bins. In the air-cushion suspension tests the abrasion damage ranged from 0.6 to 5.0% for all of the bins. The majority of the abrasion damage (75.0 to 100%) was classified as category A abrasions. The percent of fruit that graded Extra Fancy was significantly different among suspension, bin type, and the interactions suspension × bin and suspension × distance. Fruit transported on the steel-spring suspension graded from 71.3 to 96.9% Extra Fancy compared to 93.8 to 100.0% on the air-cushion suspension. The percent Extra Fancy fruit in the plastic bins was significantly higher in the hardwood bins for the steel-spring suspension tests. However, air-cushion test results were similar and no significant difference was found among the means.

Results from these tests clearly indicate the advantage of using air-cushion suspension semi-trailers and plastic bins. To determine the differences in the grade of fruit transported on the different semi-trailers and in the various bin types, the percent of apples that are in contact with the sidewalls has to be considered. Burton et al. (1989) estimated that in a standard pallet bin, approximately 25% of the apples are in contact with the sidewalls. An analysis of tables 1 and 2 shows that the overall difference (average of all bins, middle and side fruit, and trip distances) in the percent of Extra Fancy fruit for apples transported on steel-spring versus air-cushion semi-trailer was 3.5%.

The benefits of using plastic bins is more apparent when transporting with steel-spring suspension semi-trailers. If we use the hardwood bin and the steel-spring suspension as a standard, the difference in Extra Fancy fruit for each bin compared to the hardwood is 5.8% for Dolav, 5.1% for MacroBin, and 1.7% for plywood.

The benefits of using air-cushion versus steel-spring suspension and plastic versus wood bins is dependent on many factors. One of those factors would include a variety's resistance to bruise and abrasion damage. In our tests a variety was used that is very susceptible to damage. The fruit was also positioned at the rear of the trailer where acceleration levels are higher compared to the middle. If a variety such as Red Delicious were used or the fruit had been positioned in the middle of the trailer, the differences in damage levels and grade between bin types and suspension systems would probably be less. As transport distances increases, particularly on rough road conditions, the benefits of using air-cushion versus steel-spring suspension semi-trailers and plastic versus wood bins would increase.

Highway Vibration Data

The vibration data (transformed into PSD plots) collected during the short trip tests for the right and left rear of the steel-spring and air-cushion suspension semi-trailers are shown in figures 3 and 4. The plots for the right and left side of the steel-spring trailer had similar PSD levels throughout the frequency spectrum. Predominant PSD levels were found at frequencies of 4 and 20 Hz for both the right and left side of the steel-spring trailer. Similar PSD curves for the entire frequency spectrum were also found in both the right and left side of the air-cushion trailer. At frequencies between 2.5 to 9 Hz and 20 to 70 Hz the PSDs for steel-spring compared to air-cushion is generally greater by a magnitude of 1.0 to 1.5. Lower frequency levels are critical as previous research by Armstrong et al. (1992) found that apples start resonating in bins around 6 to 7 Hz, therefore, one could expect higher damage levels for fruit transported on steel-spring suspension trailers. Vibration data collected for each suspension system during the long trip tests produced PSD plots that were nearly identical to the PSD plots for the short trips (data not shown). The composite PSD curve used as the input for the computer-driven vibration table during the 60-min simulated highway transportation test is presented in figure 5.

Bin Resonance

The bin resonance tests revealed that the resonant frequency for the utility apples in the five commercial bins ranged from 7 to 15 Hz (table 3). The starting resonant frequency is a good indication of the bin bottom stiffness. Armstrong et al. (1991) demonstrated that utility apples in a bin with a rigid bottom started to resonate at a frequency of 10.5 Hz. In these tests the Dolav and the three stringer pallet bin had higher starting resonant frequency (8.5 Hz) compared to the other three bins. The peak resonance (frequency where the apples have the most movement; i.e., are bouncing the highest) was the lowest for the two stringer hardwood bin (8.0 Hz) and the highest for the Dolav bin (11.0 Hz). As the frequency increased above

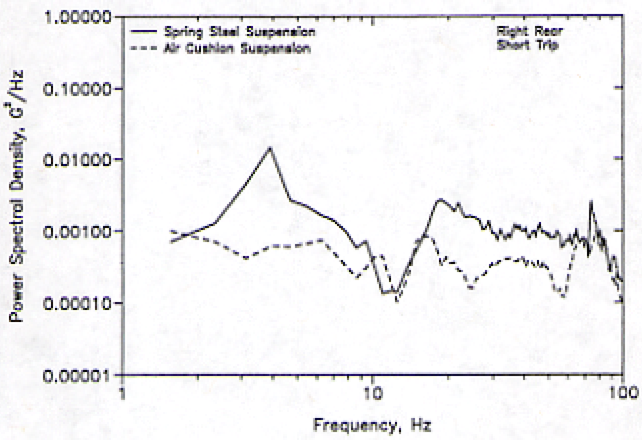

Figure 3–PSD curves derived from the vibration data collected on the right side of steel-spring and air-cushion suspension semi-trailers.

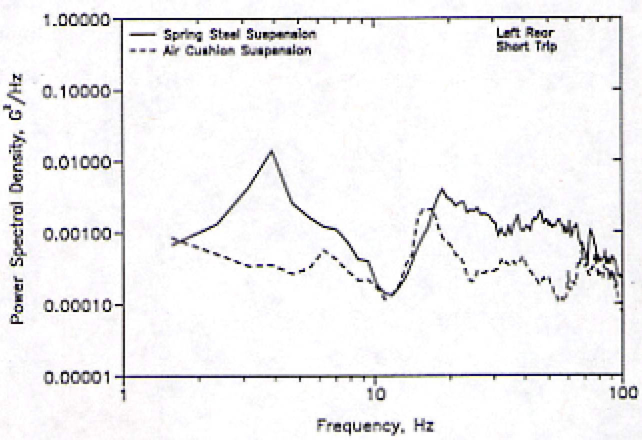

Figure 4–PSD curves derived from the vibration data collected on the left side of steel-spring and air-cushion suspension semi-trailers.

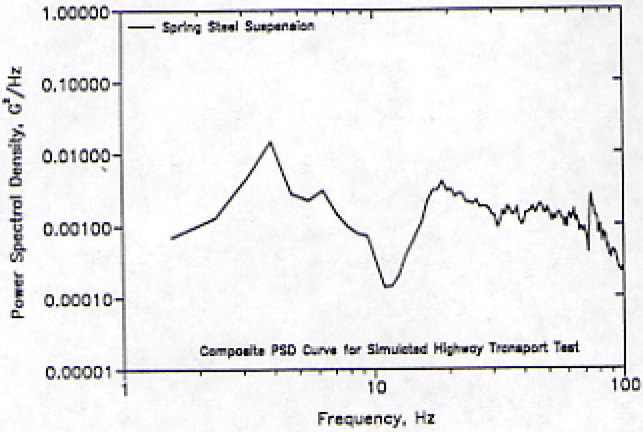

Figure 5–Composite PSD curve used in the simulated highway transportation test.

15 Hz, the movement of the apples in all bins decreased and the apples started to rotate. The frequency range for the rotational effect started at 16 Hz and continued until approximately 28 Hz.

Simulated Highway Transportation Test

Fruit quality from the 60-min simulated transport trip resulted in a wide range of abrasion damage among the five bins (table 4). Other fruit quality variables such as the percent of fruit that was undamaged, bruised, and Extra Fancy is not shown due to uncontrolled circumstances. The vehicle which transported the fruit from the test site back to the cold storage was involved in an accident, which resulted in some of the fruit being bruised. Bruises caused by the simulated test and those from the accident were not distinguishable, therefore, only abrasion damage results are presented.

Abrasion damage from the simulated trip was very similar to the damage from the highway test (steel-spring suspension, long trip distance). Abrasion damage was slightly higher in the highway tests for each of the bins tested with the exception of the plywood bin. Damage on test fruit in the middle of the bin compared to the side was typically much lower for each bin. The data also suggest from both simulated and highway tests that the bin surface condition is an important factor in the amount of abrasion damage on the fruit that is in contact with the sidewalls. In the simulated tests the sidewall abrasion damage in the wooden bins ranged from 36.3% for the plywood bin to 58.8% for the two stringer Michigan hardwood bin. The

Table 3. Range of resonant frequency for five bins tested on a computer-controlled vibration table using firm utility Red Delicious apples

Bin Description	Range (Hz)	Peak Resonance
Two stringer Michigan hardwood	7.0-14.0	8.0
Three stringer pallet Michigan hardwood	8.5-13.0	9.5
Dolav model 1000	8.5-15.0	11.0
MacroBin model 32FV	7.5-12.0	10.5
West coast plywood	7.0-13.0	9.5

Table 4. Abrasion damage from the 60-min simulated transport trip and actual highway tests (steel-spring suspension, long trip distance)

Bin Type	Simulated Test, ABR (%) Middle of Bin	Simulated Test, ABR (%) Side of Bin	Highway Test ABR (%) Middle of Bin	Highway Test ABR (%) Side of Bin
Two stringer Michigan hardwood	2.5	58.8	3.8	62.5
Three stringer pallet Michigan hardwood	1.3	57.5	1.3	67.5
Dolav model 1000	0.0	17.5	2.5	18.1
MacroBin model 32FV	0.0	0.0	1.9	5.0
West coast plywood	0.0	36.3	2.5	33.8

plastic bin sidewall abrasion damage was 17.5% for the Dolav bin and 0.0% for the MacroBin.

The results from this test indicate that simulated transport tests will provide results similar to actual highways tests, however, the PSD curve used as the input for the vibration table should be derived from vibration data collected during actual highway conditions. In our tests we selected the most extreme case that would provide for a wide range of damage. The use of bins with smooth interior surfaces will greatly reduce the amount of abrasion damage during bin transportation operations.

Summary and Conclusions

The results indicate that the U.S. apple industry can reduce apple damage and maintain higher quality if bulk apples are transported in plastic bins and on semi-trailers equipped with air-cushion suspension systems. The plastic bins were less affected by suspension type than were the wooden bins. Abrasion damage in the hardwood and plywood bins was higher compared to the plastic bins when transported on the steel-spring semi-trailer. Bin surface condition is an important factor in the amount of abrasion damage. On air-cushion the benefit is less. Overall, an increase of 3.5% of the fruit graded Extra Fancy on air-cushion compared to the steel-spring semi-trailer.

The vibration data collected during each transport test revealed that at frequencies between 2.5 to 9 Hz and 20 to 70 Hz the PSD's for the steel-spring semi-trailer were greater by a magnitude of 1.0 to 1.5 compared to the air-cushion. The results from the highway tests confirm that vibration levels in steel-spring semi-trailers cause more damage to apples than air-cushion systems.

The range of resonance frequency of a bin is important when transporting apples on steel-spring suspension trailers. A higher starting resonance is an indication of a stiffer bin bottom. The peak resonance (frequency where the apples in each bin have the most relative movement) was higher for both the plastic bins indicating stiffer bottom floors compared to the wooden bins.

The PSD curve used as the input for the computer-controlled vibration table in the simulated highway transport tests provided similar apple abrasion damage results compared to actual highway tests. Additional tests are needed to verify the data collected from the air-cushion tests.

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